# Measurement performance of high-accuracy low-pressure transducers

A. P. Miiller

**Abstract.** A systematic study of measurement performance is described for several different types of transducer including capacitance diaphragm gauges (CDGs), quartz Bourdon gauges (QBGs), quartz resonant gauges (QRGs), and two types of MEMS (MicroElectroMechanical Systems) sensors – piezoresistive silicon gauges (PSGs) and resonant silicon gauges (RSGs). Key factors limiting their performance were identified as random noise, short-term instabilities in zero-pressure readings, long-term shifts in a transducer's calibration with time and, in the case of heated gauges, the effect of thermal transpiration. The study determined that CDGs, QBGs, and QRGs have superior noise-limited pressure resolution (about 1 part in $10^6$ of full scale), though CDGs, because of their availability with lower full-scale ranges, have the best absolute pressure resolution. Analyses of calibration data indicated that QBGs, QRGs and RSGs have the best long-term stability, with average calibration shifts of the order of 1 part in $10^4$ per year, one to two orders of magnitude smaller than those observed for CDGs.

## 1. Introduction

Measurement performance of high-accuracy low-pressure transducers has been the subject of ongoing study at the National Institute of Standards and Technology (NIST), primarily because of the important role they play in the operation of primary standards for vacuum, low pressure, and low-flow rates. These transducers serve both as check standards and transfer standards, and so an accurate knowledge of their performance limitations is critical not only in their own use but also in the assessment of overall uncertainties of the NIST primary vacuum standards.

The first systematic study at the NIST, published in 1985 [1], presented somewhat limited calibration data on seventeen CDGs. A more comprehensive study [2] was published twelve years later and included a considerable amount of additional performance data that had been accumulated at the NIST on seventy-nine CDGs.

This paper is an update of the latter study. It provides a comprehensive review of major factors limiting the measurement performance of low-pressure transducers of the type frequently used by calibration laboratories as transfer standards. In addition to supplementing the data on CDGs (data from ninety-one CDGs are now included), this paper also presents performance data on other high-accuracy transducers such as quartz Bourdon gauges, quartz resonant gauges, piezoresistive silicon gauges, and resonant silicon gauges. Depending on the gauge type, their full-scale (FS) ranges extend from as low as 13 Pa to about 130 kPa.

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## 2. Description of the transducers

The different types of transducer considered in this study belong to a class of low-pressure gauges that measure pressure directly as a force per unit area by converting a deflection or a strain in some mechanical element into an analogue or digital output. The gauges are inherently differential in that they measure differences between an unknown applied pressure and a reference pressure. Absolute gauges are constructed by evacuating the reference side of the sensor to $< 10^{-5}$ Pa and sealing it, often with a chemical getter, to maintain a low reference pressure.

In modern CDGs [3, 4], the deflection (actually the curvature) of the diaphragm is sensed by two capacitor electrodes deposited as concentric metallic films on a ceramic substrate. The unequal changes in capacitance sensed by the two electrodes are converted into a dc voltage output by a capacitance-bridge circuit. The sensor capsule is mounted inside a heated aluminium shell controlled at an elevated temperature (usually near 45 °C), primarily to attenuate the effect of changes in room temperature on the stability of the zero-pressure reading.

In the QBGs [5], the deflection (actually winding or unwinding) of a fused-quartz helical tube is converted into an electrical signal by using a mirror attached near its closed end to reflect a light beam on to two identical photocells. Unequal illumination of the photocells produces an error signal that is converted to a proportional current. The current passes through force-balancing coils to maintain the mirror/quartz tube assembly in its "zero" position. The current, which is proportional to the differential pressure, is converted to a dc output voltage by a precision resistor. The sensor capsule is mounted in an aluminium/steel housing controlled at about 50 °C to attenuate the effect of changes in room temperature on the stability of the zero-pressure reading.

The operation of low-pressure transducers at elevated temperatures can give rise to an undesirable effect known as thermal transpiration [6, 7] when used to measure absolute pressures below 100 Pa (see Section 3). Hybrid systems have been developed at the NIST that minimize this effect by controlling the transducer temperature close to room temperature. This involves mounting the transducers inside thermal enclosures that have thermoelectric (TE) modules with bidirectional heating/cooling capability. An external power supply and bridge circuit used to drive the TE module are able to control the interior temperature of the enclosure near 23 °C, to within ±20 mK for room temperature changes of up to a few degrees.

In the QRGs [8], a bellows or a Bourdon tube is used to convert an input differential pressure into axial strain in a crystalline quartz resonator. Changes in pressure are detected by measuring the strain-induced changes in resonant frequency of the resonator. Residual thermal effects are compensated by means of an internal quartz-crystal temperature sensor. Self-contained electronics provide dual-frequency outputs (one for pressure, the other for thermal compensation).

MEMS-type pressure sensors are manufactured by silicon micromachining techniques that produce silicon diaphragms nominally a few millimetres square by a fraction of a millimetre thick. In PSGs [9], dopants are diffused into the silicon in selected regions of the diaphragm to form piezoresistors. Changes in differential pressure across the diaphragm are determined by measuring strain-induced changes in resistance using simple Wheatstone-bridge circuitry. In the RSGs [10], two single-crystal silicon resonators are encapsulated in vacuum microcavities micromachined on to the surface of the silicon diaphragm. Changes in differential pressure across the diaphragm are determined by measuring strain-induced changes in the two resonant frequencies. Both MEMS-type gauges use temperature compensation to minimize thermal effects.

## 3. Factors limiting measurement performance

The measurement performance of low-pressure transducers is limited by several factors. At the lowest pressures the most important of these are random noise, short-term (hours to days) instabilities in zero-pressure readings and, for heated gauges, thermal transpiration at absolute pressures below 100 Pa. At higher pressures performance is limited by long-term shifts in calibration with time (months to years).

Random noise limits the smallest pressure change that can be resolved by a transducer. A measure of the noise-limited *pressure resolution* is given by twice the standard deviation of repeated readings at a stable pressure, which is plotted in Figure 1 as a function of transducer FS range. As these data show, the resolution of different transducers tends to scale linearly with their FS range: CDGs at about 1 part in $10^6$ of FS, quartz-based transducers at about 1 part in $10^6$ to 3 parts in $10^6$ of FS, and MEMS-type transducers at about 4 parts in $10^6$ to 10 parts in $10^6$ of FS. Because of their availability with lower FS ranges, CDGs have the best absolute pressure resolution among the transducers.

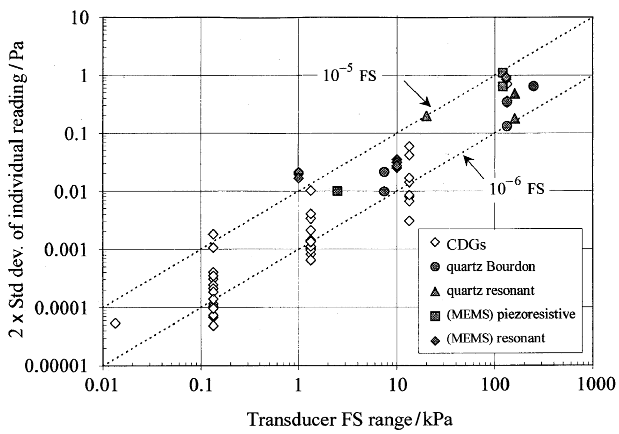


**Figure 1.** Noise-limited pressure resolution for different types of low-pressure transducer.

The zero instabilities in transducers manifest themselves primarily in two ways. They appear either as *zero shifts* that correlate directly with changes in room temperature, or as *zero drifts* that vary randomly in both sign and magnitude and are probably due to drifts in electronics and/or mechanical structure of the gauge. This behaviour is illustrated in Figure 2, which presents zero-pressure readings of three 1330 Pa CDGs taken over a period of nearly three days after they were initially zeroed (system residual pressure $10^{-4}$ Pa). As illustrated by these data, *zero drifts* cannot be easily quantified yet they are a qualitative characteristic for a given transducer, i.e. some exhibit significant zero drift while others are relatively stable. Experience at the NIST indicates that many CDGs exhibit some degree of zero drift, as do QBGs and PSGs, whereas QRGs and RSGs are quite stable.

During the course of measurements, the CDGs were also subjected to a room temperature cycle of about 2 °C. The resulting *zero shifts* are proportional to room temperature change and can be described in terms of a temperature coefficient. Figure 3 presents zero-pressure temperature coefficients for a number of transducers

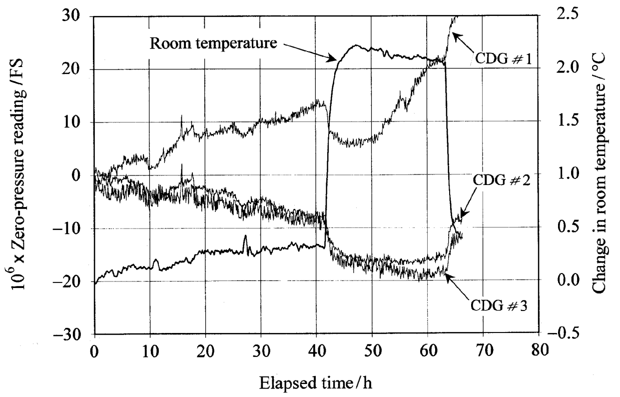


**Figure 2.** Stability of zero-pressure readings for three absolute 1330 Pa (10 Torr) CDGs.

as measured at the NIST. In general, CDGs with the lowest FS range and therefore highest sensitivity also have the largest zero-pressure temperature coefficients, though a significant variation exists among CDGs with a given FS range. The zero stability of six hybrid CDG systems appears to be better, at least on average, than that of CDGs temperature controlled with their internal heaters. Although limited, data on other types of low-pressure transducer indicate that they are two to three times more sensitive to changes in room temperature than are standard CDGs with similar FS ranges.

Changes in orientation or tilt of a transducer can also give rise to an apparent *zero shift*. For most types of transducers the effect is small: approximately 0.0001 Pa/mrad for PSGs, 0.001 Pa/mrad for CDGs, and 0.01 Pa/mrad for QBGs. However, the tilt sensitivity of RSGs is surprisingly large, about 300 Pa/mrad to 400 Pa/mrad, which is related to the use of silicon/oil interfaces between the silicon diaphragm and two sealing diaphragms in contact with the pressurizing medium. Since the performance of low-range units can be adversely affected by tilt, it is recommended that for highest-accuracy measurements RSGs should be mounted on a base with tilt adjustment and a precision level.

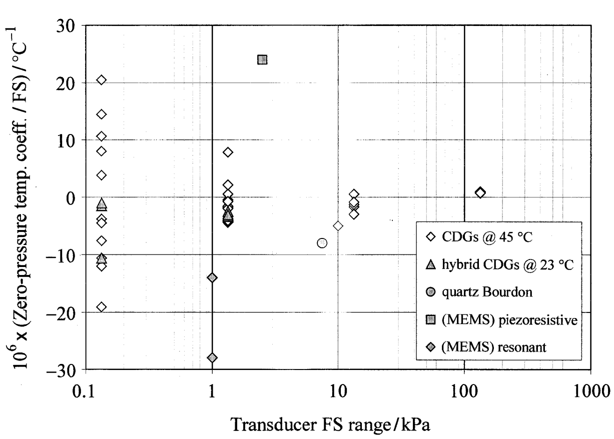


**Figure 3.** Zero-pressure temperature coefficients for different types of low-pressure transducer.

The *thermal transpiration effect* is illustrated in Figure 4, which presents several sets of data obtained during absolute-mode calibration of a 133 Pa CDG using helium and argon. The upper two sets of data show that the response of the heated CDG becomes highly non-linear as pressure is decreased and is 4 parts in $10^2$ too high at the lowest pressures. In the transition region between about $10^{-2}$ Pa and $10^2$ Pa, the gauge response is also gas-species dependent. The non-linear behaviour can be approximated by the semi-empirical Takaishi-Sensui equation [6] shown as dashed and continuous lines. The lower two data sets clearly show that controlling the CDG at near room temperature significantly reduces thermal transpiration effects.

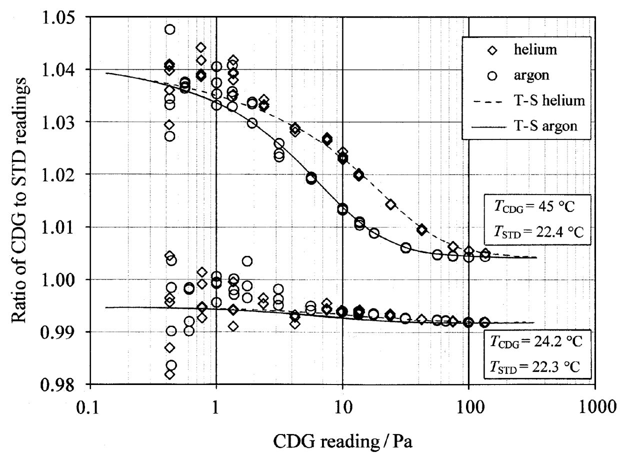


**Figure 4.** Absolute-mode calibration data for a 133 Pa (1 Torr) CDG when controlled at 45 °C and at 24.2 °C.

Over the past two decades, we have accumulated a large database at the NIST that includes 383 calibration records for ninety-one CDGs as well as more limited calibration data for the other transducer types. All transducers were calibrated with nitrogen gas by comparison with one of two NIST primary pressure standards operating in absolute mode: either the 160 kPa mercury Ultrasonic Interferometer Manometer (UIM) [11] or the 140 Pa oil UIM [12]. The uncertainties of the standards at pressure $P$ due to systematic effects are estimated as ($k = 1$)

$$[(3\,\mathrm{mPa})^2 + (2.6 \times 10^{-6} P)^2]^{1/2}$$

for the 160 kPa mercury UIM,

$$[(1.5\,\mathrm{mPa})^2 + (18 \times 10^{-6} P)^2]^{1/2}$$

for the 140 Pa oil UIM.

The *calibration instabilities* were determined by calculating shifts (average of values at 0.1 FS, 0.5 FS, and 1 FS) in the "calibration factor" (pressure standard reading/gauge reading) between successive calibrations.

The period between calibrations was typically one to two years. Figure 5 presents results for the 133 Pa CDGs as a function of calibration number; the shift for the first calibration is zero by definition. This plot exhibits three characteristics also seen in data for CDGs with other FS ranges. First, the largest shifts occur early in the calibration history. Second, the calibration changes appear as random shifts rather than a monotonic drift with time. Third, the low-range gauges belonging to our calibration customers are significantly less stable than those belonging to the NIST.

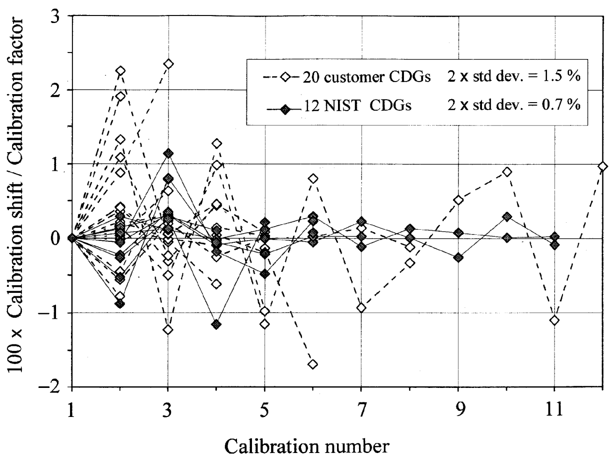


**Figure 5.** Calibration instability of 133 Pa (1 Torr) CDGs calibrated at the NIST.

**Table 1.** Calibration instabilities of absolute (A) and differential (D) high-accuracy CDGs calibrated at the NIST.

| CDG Full-scale range | Number of gauges | Number of calibrations | $2 \times$ std dev. (% shift) |
|---|---|---|---|
| *Calibration customer gauges* | | | |
| 133 Pa (1 Torr) | 20 | 83 | 1.5 |
| (A; D) | (14; 6) | (61; 22) | (1.7; 0.7) |
| 1330 Pa (10 Torr) | 20 | 78 | 0.8 |
| (A; D) | (11; 9) | (46; 32) | (0.8; 0.7) |
| 13.3 kPa (100 Torr) | 12 | 47 | 0.5 |
| 133 kPa (1000 Torr) | 8 | 22 | 0.3 |
| *NIST gauges* | | | |
| 133 Pa (1 Torr) | 12 | 63 | 0.7 |
| (A; D) | (9; 3) | (37; 26) | (0.8; 0.7) |
| 1330 Pa (10 Torr) | 12 | 66 | 0.4 |
| (A; D) | (9; 3) | (42; 24) | (0.3; 0.5) |
| 13.3 kPa (100 Torr) | 5 | 16 | 0.4 |
| 133 kPa (1000 Torr) | 2 | 8 | 0.3 |
| Total | 91 | 383 | |

A measure of calibration instability is given by twice the standard deviation about the mean shift (nominally zero). Table 1 shows that instabilities are largest for gauges with the lowest full-scale range. These gauges also show the largest difference between customer and NIST gauges. Furthermore, the 133 Pa absolute CDGs belonging to our customers are significantly less stable than their differential units. Plausible explanations for these differences may be rough handling during shipment between calibrations and/or insufficient care when venting the lowest-range absolute CDGs to atmosphere.

Figure 6 gives a comparison of calibration instabilities of the other types of transducer and CDG, in which the average absolute shift in calibration factor (for a minimum of two repeat calibrations) is plotted as a function of transducer FS range. These data show that other types of transducer have long-term instabilities that are at least an order of magnitude smaller than that for CDGs, typically less than 1 part in $10^4$ for QBGs and QRGs, about 1 part in $10^4$ for RSGs, and about 2 parts in $10^4$ for PSGs.

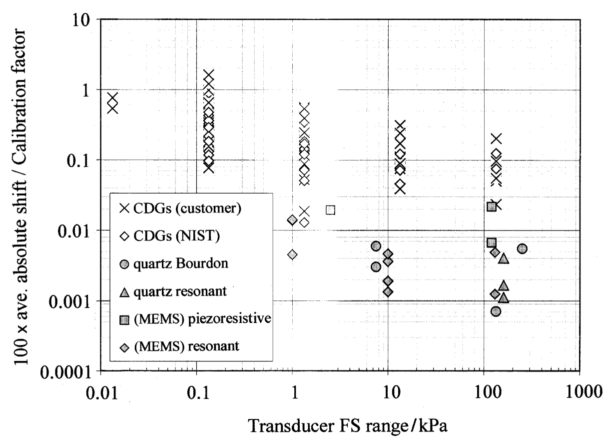


**Figure 6.** Summary of long-term instabilities of low-pressure transducers calibrated at the NIST.

## 4. Concluding remarks

Accurate knowledge of performance characteristics is essential when selecting the optimum transducer for a measurement application. However other factors, such as susceptibility to mechanical shock or to overpressure, can also be important considerations.

Although CDGs lack the long-term stability of other gauges, they continue to be the transducer of choice for many applications because of their superior pressure resolution, all-metal construction and ruggedness. The other transducers in our study have excellent long-term stability but their absolute pressure resolution is not as good as the CDGs. The quartz-based gauges have the best calibration stability but are somewhat fragile (QBGs) or are susceptible to overpressure (QRGs). The MEMS-type gauges have good calibration stability, are resistant to mechanical shock, and are only moderately susceptible to overpressure, but can be highly sensitive to tilt (RSGs).

## References


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